Static and dynamic alignment of turbomachinery

"...Good alignment reduces stress on the rotors. This means a smoother operating machine, less downtime and lower maintenance cost..."

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Alignment of turbomachinery should be given serious consideration. Poor alignment is considered to be the prime cause of vibration, which in turn could result in a catastrophic failure. Machinery today is mechanically aligned using very sophisticated methods, such as optics, lasers and excellent computer-aided mechanical tools.

People strive to obtain an alignment based on a calculated thermal growth figure that may, or may not, be close to where the machinery operates. Therefore, it is very important to determine the dynamic alignment to determine the proper static alignment. With a high percentage of vibration in turbomachinery directly caused by misalignment, the purpose of this article is to describe and advise readers about some of the methods used to correct this misalignment and provide smoother operating turbomachinery.

Many people are aware that misalignment is a prime cause of vibration in rotating machinery. Unfortunately, the majority of end-users don't concern themselves with alignment until machinery is displaying excessive vibration levels, and vibration analysis points to misalignment. Studies confirm that approximately 70 percent of vibration in rotating machinery is caused by misalignment.

What is alignment?

Alignment is more than the act of aligning, the adjusting of electronic or mechanical parts to a line or to each other. According to the Society of German Engineers, alignment also means, "the geometrically perfect arrangement of all rotating shafts and wheels." Anyone who deals with high and low speed rotating equipment must understand alignment. This machinery includes high and low speed rotating equipment in the form of turbines, generators, compressors, pumps, reciprocating compressors, marine shafting or equipment found in paper mills. Most machinery requires realignment at some time or other.

Machinery supplied by an original equipment manufacturer (OEM) usually comes with suggested static alignment figures. These figures are usually calculated thermal rise for that specific piece of equipment and may, or may not, be derived from rigorous thermal analysis. This value is usually not highly accurate but one you must use for the initial alignment.

Different alignment methods

There are various methods used to obtain this initial mechanical alignment. The most common is "the reverse dial indicator" method (Ref. 1), which entails two dial indicators mounted on opposite shafts which are read simultaneously, preferably with the coupling in place. The addition of special alignment bars (Ref. 2) has improved the reverse dial indicator method as both indicators can be read with ease as the shafts and coupling rotate through 360 degrees.

There are also laser optic systems available which automatically convey misalignment data to a microprocessor. The systems generally consist of an emitter/receiver laser unit and a beam return prism or two transmitter/detector units. The laser is mounted on one shaft, the prism on the other or a transmitter/detector unit can be mounted on each shaft. When all data the distance from the shaft end to the unit support feet, etc. has been fed into the computer, you are ready to align.

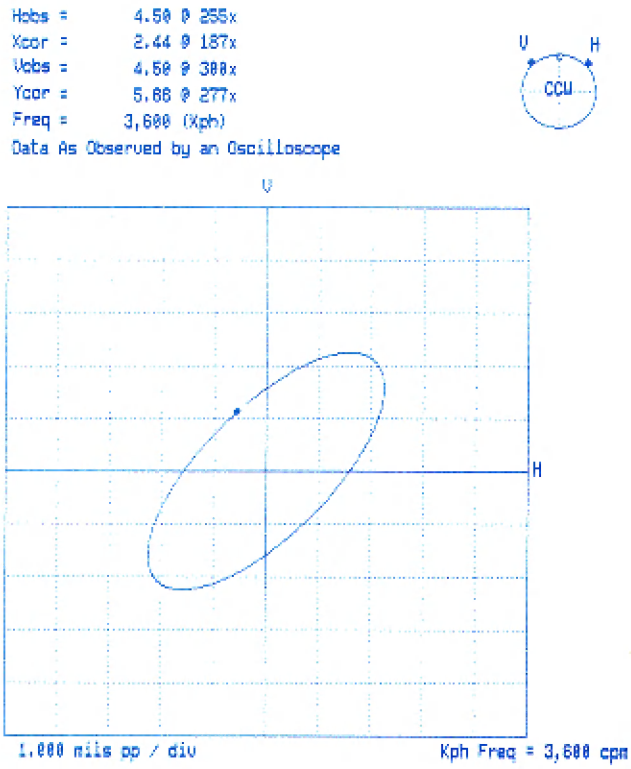


Figure 1

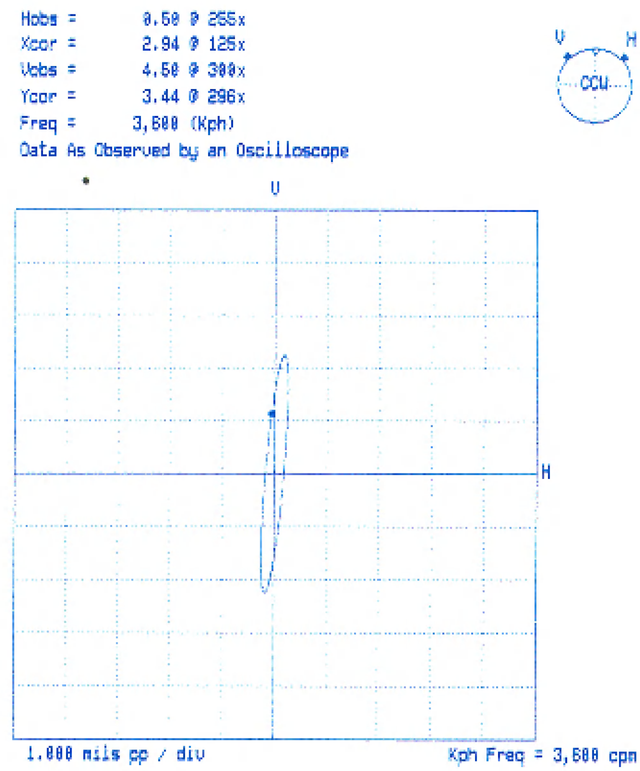


Figure 2

The laser units are especially good when you have an extremely long spool piece and are excellent tools for aligning large vertical pumps.

Where should you initially place the machinery? We have already stated that the alignment numbers supplied by the OEM are sometimes questionable as they are based on a calculated thermal rise. Equipment does not always conform to these alignment numbers, but these numbers are a place to start until the actual thermal rise has been confirmed. If a lateral movement is given for a steam turbine, compressor, boiler feed pump or similar piece of rotating machinery, it would be better to set it "straight on" until the actual movement can be confirmed. This reasoning is given because piping must be attached to the machinery. Improperly installed piping induces pipe strain, which in turn moves the machinery out of alignment and, in most situations, increases vibration levels. Incorrect piping can also twist a case, causing internal problems.

A gear case, especially the fabricated style of case, is the one piece of machinery in a train which very rarely grows according to predictions. The one-piece-cast case lacks the vertical or lateral movement found in a fabricated case. Often there is no logical explanation for this vertical and horizontal movement as measured. Theoretically, the oil temperature would need to be in the 500°F (260°C) range to confirm the rise recorded. In other situations, the observed twisting effect is caused by oil spraying or splashing on internal surfaces. This twisting does not promote good tooth contact and, on occasion, has caused the gear teeth to chip at their outer ends. It also increases vibration levels.

The fact that good alignment can reduce vibration has been established by controlled testing and also by necessity in correcting vibration induced by misalignment in a field problem. The controlled test involved a motor and compressor that were in proper alignment when in a fully-loaded operational condition. At this condition, the motor was moved horizontally in small increments, and the change in vibration level notably increased as the misalignment increased.

The field problem was on a 6000 HP motor, gear and compressor. This unit had been realigned using data from a cold/hot optical alignment study and had been in operation for approximately three months. The highest level of vibration was between the gear and compressor and was 0.4 mils peak-to-peak at 10,400 rpm. The vibration increased during a graveyard shift and by 8:00 AM had reached 3.0 mils peak-to-peak at running speed frequency (1X). When the alignment was checked optically at 12:00 noon, the vibration level was 4.0 mils peak-to-peak, and the compressor was out of horizontal alignment by 0.062 inch (1.58 mm).

This misalignment was also confirmed by the shape of the Orbits, before and after the compressor moved (Figures 1 & 2). The misalignment was caused by pipe strain induced on the compressor by failure of the spring hanger supporting the suction and discharge piping to and from the compressor. When the spring hanger was reinstalled, and the springs adjusted to the proper tension, the compressor moved towards its original alignment.

Figure 3

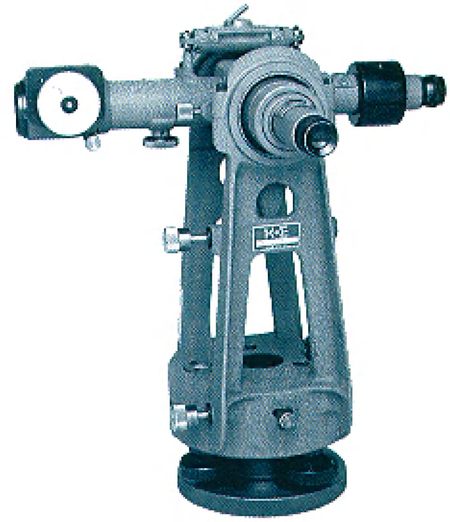


Figure 4

However, it was still 0.040 inches (1.02 mm) out of alignment when the tension was correct.

The production department would not allow the compressor to be shut down for realignment. Therefore, there was no choice but to do an alignment move while in operation. This was done very carefully with dial indicators mounted at each corner of the compressor and with the optical alignment transits zeroed to their established lines of sight. With each movement toward the original alignment, vibration levels decreased until the unit was once again in position and the vibration level was back to 0.4 mil peak-to-peak. This realignment exercise was observed by some high level plant managers. One of the managers felt that if the compressor were moved further, the vibration would cease. When this was done, he was surprised to see the level increase and became a firm believer that vibration and alignment were directly connected to each other.

For safety reasons, machinery should ***not*** be moved while it is in operation, especially if the alignment has to change vertically. Horizontal changes can be done very carefully, provided there is no excessive pipe strain. However, there is no question that the ideal way is to shut the unit down and then realign the machine.

It is important to know the alignment when turbomachinery is in its dynamic (hot/normal) operating condition. Otherwise, the proper static (cold/shutdown) mechanical alignment cannot be obtained. There are several ways to obtain this dynamic (hot) alignment data. Of the different methods we will discuss, the optical alignment method gives the best overall results.

Methods for determining hot alignment

The optical method applies optical tooling technology to the thermal growth and movement (shaft alignment) of rotating machinery. This involves the use of precision optical instruments (Figures 3 & 4) to establish precise, defined lines of sight that can be repeated from one optical check to another. An optical scale holder system, capable of the same precise repeatability, along with the accurate documentation of scale locations, is used in conjunction with the instruments. The optical alignment technique has proven its usefulness in original installation, repair and maintenance of turbomachinery.

There are other methods used to determine "hot" alignment. One is the Charlie Jackson method of using proximity probes mounted on water-cooled stands (Figure 5) (Ref. 3). These stands are located at each end of each component in the machine train, with a minimum of two proximity probes mounted on each stand to relate the vertical and horizontal movements. The results can then be plotted graphically. This method is a very good way to monitor the alignment of a train, especially if the unit is exposed to the elements, sunlight, heavy rain, snow, etc. Charlie Jackson used this method during his tenure with Monsanto at Texas City, Texas. It is valuable to compare the proximity probe data to the optical data.

The "Dodd Bar" method (Figure 6) (Ref. 4) uses proximity probes mounted on bars located on each unit at each coupling location in a train. One bar contains mounted probes which are referenced to the other bar for the probe gap. Movement of the units is measured by the change in probe gap, and the relative alignment of the train is calculated and plotted. When actual problem conditions are studied, there is a close correlation between the alignment bars and optical readings.

Another method is the Acculign System, sometimes known as benchmark gauges (Figure 7) (Ref. 5), which uses a spring-loaded telescoping column with spherical seats to accept tooling balls mounted on the machinery and installed in the concrete foundation Angular measurements and displacement readings are obtained from static

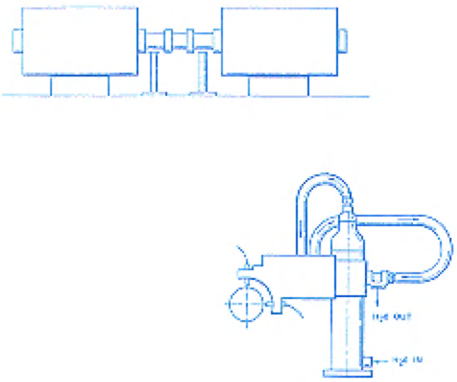


Figure 5

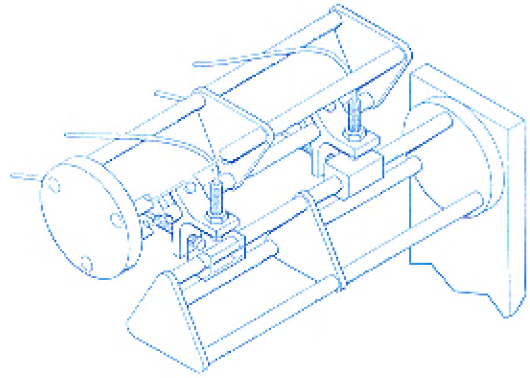


Figure 6

(cold) to dynamic (hot) and the suspected movement of the unit calculated, both by graphical plotting and by calculator programs set up for this method of alignment. This method, in conjunction with an optical system, produces good results.

The preceding systems are different, but they all produce good results. Therefore, if you don't have a system, get one.

what can we live with?

The most common question asked when misalignment is present is "What can we live with?" The manufacturer of the machinery will tell you one thing; the coupling manufacturer will tell you another, and Bently Nevada Corporation, as a service company, may tell you something else.

A coupling manufacturer will advise that their coupling can withstand misalignment up to "a figure," which is normally large and varies among different manufacturers. The figure they recommend is normally true, and the coupling will withstand that amount of misalignment. Meanwhile, what does this misalignment do to your bearings, labyrinths, seals, etc.?

The coupling length is the key factor in determining how much misalignment can be tolerated. Since there are no specific figures, you must have guidelines within which to work. A good figure is 0.00025 inch (.006 mm) for each inch (25.4 mm) of coupling length. This figure can normally be achieved on realignment. Otherwise, an adjustment may be required, especially on old installations. If the 0.00025 inch (.006 mm) per inch (25.4 mm) cannot be achieved, the factor can be raised to 0.0005 inch (.013 mm) per inch (25.4 mm) of coupling length. This figure ***can*** be achieved, and vibration due to misalignment would not be expected to occur from alignment that was within this tolerance.

One should not live with misalignment that exceeds 0.001 inch (.025 mm) per inch (25.4 mm) length of coupling. Bently Nevada Corporation can advise a customer about the best alignment for his equipment, but cannot demand that he realign or work to a suggested tolerance. The main criteria is, of course, the level of vibration, in which case an alignment to suit acceptable vibration levels must be achieved.

One of the best alignment charts produced is by John Piotrowski (Figure 8). I suggest you obtain a copy of his "Shaft Alignment Handbook," an excellent publication (Ref 6).

Optical alignment of turbomachinery from a cold to hot state has been common in the petrochemical industry for over twenty years. Optical alignment has been used in the power industry for several years, primarily on boiler feed pumps, due to a rash of coupling failures, shaft cracks and shaft failures. The majority of the failures were caused by misalignment with 1X vibration frequency being prominent. The misalignment was again primarily the result of pipe strain causing excessive movement of the pump.

Power industry

In the power industry, stub shafts or directly-coupled shafts are used between turbines and generators and are, therefore, a prime source for shaft cracks. Alignment is critical in this industry; ironically, there is a great lack of alignment information. Bently Nevada is researching the alignment of large power trains to determine what the desired operating or running alignment should be. In any piece of machinery, the thermal rise can be calculated. However, the answer to this calculation has been missed on many occasions, making it more advantageous to measure the proper operating alignment.

Throughout the world, the power industry typically uses the low pressure turbine as a starting point and calculates the sag or catenary curve of the rotor, which naturally leaves the coupling faces out of parallel. By installing a coupling, stub shaft or connecting shafts directly and then ensuring that the faces are parallel, we now have the beginning of a "big banana" (Figure 9). A "big banana" can be described as a power train, consisting of two LP turbines, an IP turbine, a HP turbine and a generator and exciter which is one extremely long catenary curve. During optical thermal growth studies of power trains, it has been found that from a static (cold) shutdown condition to the dynamic (hot) operating condition, the "banana" remains and its condition merely flattens very slightly.

Changes are now being made in the alignment of power generation units,

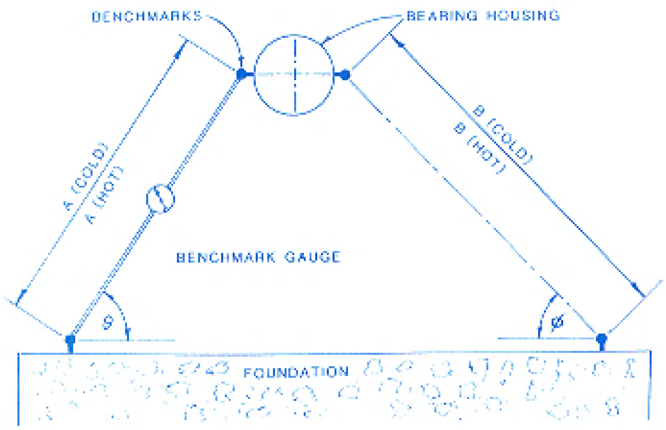


Figure 7

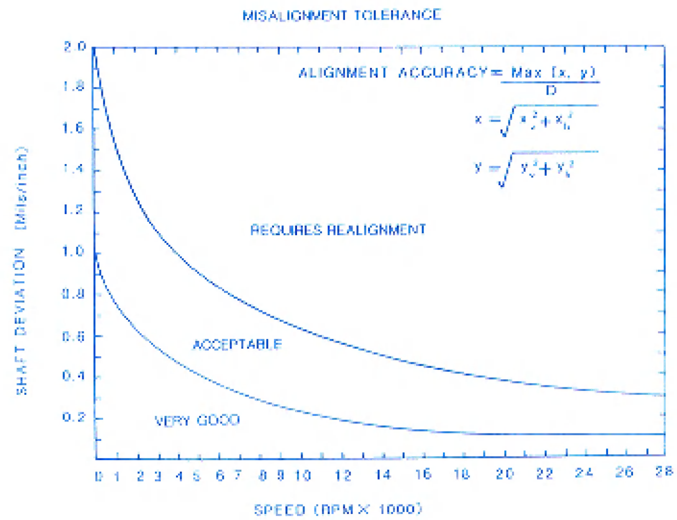


Figure 8

especially the higher megawatt units which may consist of three LP turbines, one double flow HP turbine, a generator and an exciter or alterex (depending on the manufacturer). All of the LP bearings, plus the inboard HP bearing and the inboard generator bearing, are generally set at the same elevation. This will vary if you have an IP turbine rather than the double flow HP turbine and a generator/alterex (Figure 10).

Based on static (cold) to dynamic (hot) optical thermal growth data on record, other changes have been suggested. However, it is very difficult to convince the power generation companies to vary from the OEM alignment standard, even when they are experiencing excessive vibration levels on their machinery. Nevertheless, some power companies have changed their machinery alignments to correspond to the observed data.

On small turbine generator units showing high levels of vibration and where alignment is suspected as the cause, it is generally the excessive height of the generator outboard pedestal that is actually the cause. This alignment is even more critical when the unit consists of only three bearings, with the middle bearing either part of the turbine or part of a speed-reducing gear. Cracks have appeared in both the generator and turbine shafts directly behind the coupling flange, due primarily to the excessive height of the outboard generator pedestal bearing.

In the power industry, one of the prime uses of the optical method of alignment is to set diaphragms in the turbines as it is much quicker and accurate than the old piano wire method.

When using an optical alignment telescope with a target installed in the diaphragm, the diaphragm can be removed, adjustments made and the diaphragm reinstalled. With the piano wire method, the wire must be removed to lift out, adjust and reinstall the diaphragm, and the wire needs to be reinstalled and reset each time a diaphragm requires adjustment.

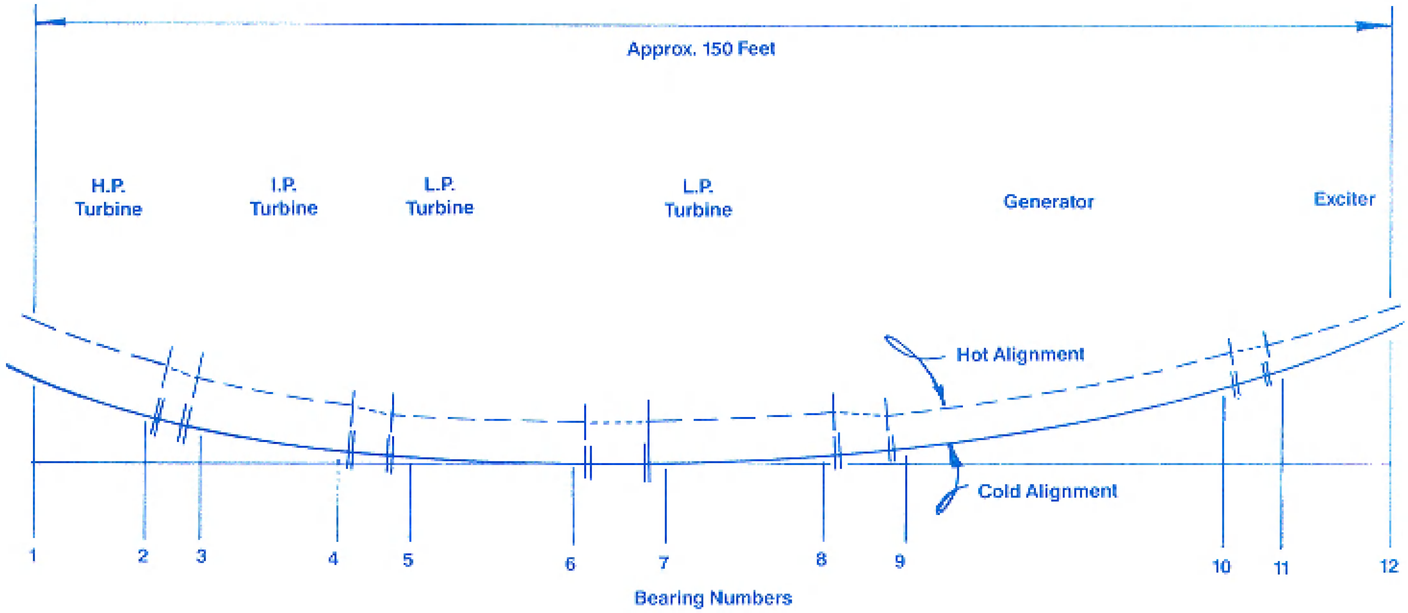
The alignment laser is another alignment method. Lasers aren't extensively used for the alignment of turbomachinery from a static to dynamic condition. Many people think a laser is more accurate than the optical method, but actually they are very comparable. The optical method is preferable over a short distance (50 feet) and the laser method is preferable over longer distances.

A power train normally consists of an HP and IP turbine, two LP turbines, a generator and an exciter, which adds up to twelve bearings. The Number 1 bearing and the Number 12 bearing would typically be 150 feet (46 metres) to 200 feet (61 metres) apart. This is a good alignment laser application, especially if the Number 1 and 12 bearings are used as the references and all the intermediate bearings are aligned to that referenced laser beam. Of course, the catenary curve must be within the range of the laser. In other words, the Number 1 and 12 bearings could not be at an elevation that was out of the range of the laser compared to the lowest LP bearing. All rotors would have to be removed to accomplish this, and that rarely occurs.

This brings us back to a point made earlier; the calculated position of the intermediate bearings is a static (cold) position. What is the alignment of the bearings while in operation?

In the power, petrochemical, gas transmission and other industries, the alignment laser can be used to align something that has a bore. Examples are a turbine with the rotor removed, a plastic extruder with the feedscrew removed or a reciprocating engine with the crankshaft removed. These machines can be aligned more quickly using optics as they are all short length items and it is quicker and easier to set up optics. There are many situations when the optical method would be preferred over the laser method and vice versa. It all depends on the situation and, in some cases, your preference.

There are several ways to observe a machine's dynamic response to a misalignment condition. If machines use hydrodynamic bearings for rotor support, an orthogonal pair of noncontacting probes is typically used at each bearing for both machinery monitoring and for diagnostic purposes. Using these probes, the rotor's orbit or shaft centerline motion can be directly



Typical Calculated Alignment of Power Train

Figure 9

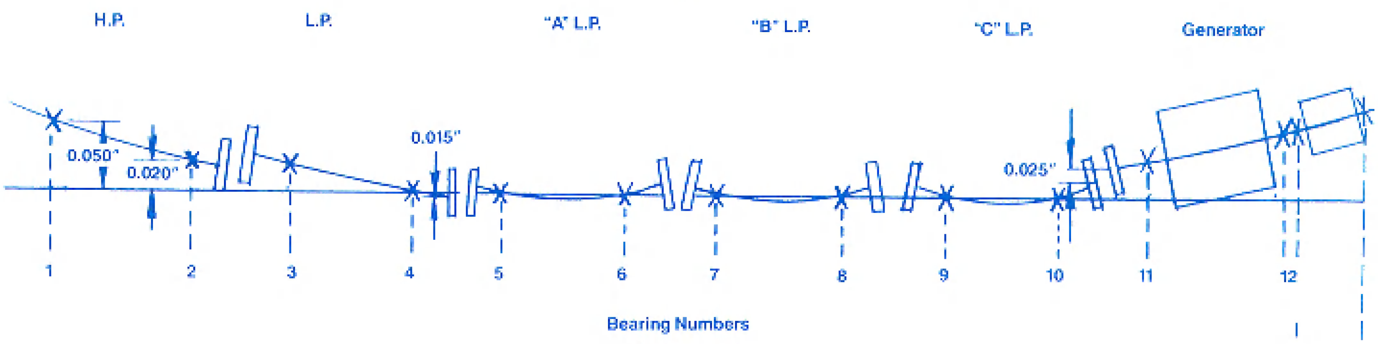


Figure 10

observed, allowing an analyst to determine the degree of preloading. Preloads are defined as unidirectional, steady state forces acting radially on a rotating element. Machine-to-machine misalignment is one type of preloading. Thus, the orbital pattern represents the direct response of the rotor. If it is abnormal, indicating a preloaded condition, the static alignment can, and should, be investigated.

Another common method of detecting a machine's response to a preload is through observation of a shaft's position in its bearing using proximity probes. Due to normal steady state forces acting on a rotor system, a rotor will move to an equilibrium position within the constraints of its bearing. If the rotor is acted upon by other loads, such as misalignment, then the rotor will respond to these loads by moving to another location. The change in position will vary depending upon the strength and direction of the preload force. Like changes in the orbital pattern, changes in the Shaft Centerline position merit investigation with machine-to-machine misalignment being one of the possible forces causing the change.

Conclusion:

Good alignment reduces stress on the rotors. This means a smoother operating machine, less downtime and lower maintenance cost. If a machine has been properly aligned and optical data has been recorded, and vibration levels subsequently increase, it is a simple matter to check the alignment and determine if misalignment is the cause of the change in vibration levels.

Once cannot overemphasize the importance of alignment in the world of turbomachinery. It also plays a big part in the reciprocating compressor and engine worlds. Therefore, think alignment when your Orbit looks flat. ■

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